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Close to the Dredge: Precise X-ray C and N Abundances in λ Andromeda and its Precocious RGB Mixing Problem

Jeremy J. Drake¹, B. Ball¹, John J. Eldridge², J.-U. Ness³, Richard J. Stancliffe⁴

Smithsonian Astrophysical Observatory, MS-3, 60 Garden Street, Cambridge, MA 02138, USA. Email: jdrake@cfa.harvard.edu

Institute of Astronomy, University of Cambridge, Madingley Road, Cambridge CB3 0HA, UK. Email: jje@ast.cam.ac.uk

European Space Agency, XMM-Newton Observatory SOC, SRE-OAX, Apartado 78, 28691 Villanueva de la Cañada, Madrid, Spain. Email: Jan-Uwe.Ness@sciops.esa.int

Centre for Stellar and Planetary Astrophysics, School of Mathematical Sciences, Monash University, Melbourne, VIC 3800, Australia. Email: richard.stancliffe@monash.edu

ABSTRACT

Chandra LETG+HRC-S and *XMM-Newton* RGS spectra of H-like C and N lines formed in the corona of the primary star of the RS CVn-type binary λ And, a mildly metal-poor G8 III-IV first ascent giant that completed dredge-up ~ 50 Myr ago, have been used to make a precise measurement of its surface C/N ratio. We obtain the formal result $[C/N]=0.03\pm0.07$, which is typical of old disk giants and in agreement with standard dredge-up theory for stars $\lesssim 1M_{\odot}$. In contrast, these stars as a group, including λ And, have $^{12}C/^{13}C \lesssim 20$, which is much lower than standard model predictions. We show that the abundances of the old disk giants are consistent with models including thermohaline mixing that begins at the red giant branch luminosity function “bump”. Instead, λ And indicates that the $^{12}C/^{13}C$ anomaly can be present immediately following dredge-up, contrary to current models of extra mixing on the red giant branch. In the context of other recent C and N abundance results for RS CVn-type binaries it seems likely that the anomaly is associated with either strong magnetic activity, fast rotation, or both, rather than close binarity itself.

Subject headings: stars: evolution — stars: abundances — stars: activity — stars: coronae — stars: late-type — X-rays: stars

1. Introduction

When a low-mass star ($0.8 - 2M_{\odot}$) evolves off the main sequence and up the red giant branch (RGB), its outer convective envelope extends inward, probing the CN-processed region of the hydrogen-burning core and propagating the processed material up to the stellar surface. Standard stellar evolution models predict this “dredge-up” to result in a decrease of the surface $^{12}\text{C}/^{13}\text{C}$ and $^{12}\text{C}/^{14}\text{N}$ ratios on the stellar surface (Iben 1967). While an extensive body of observational evidence grew demonstrating that such abundance changes do indeed occur, the changes observed were often more extreme than evolutionary model predictions (see, e.g., reviews by Iben & Renzini 1984; Charbonnel 2005; Chanamé et al. 2005). The more salient disagreements were for metal-poor field and globular cluster giants, for which the $^{12}\text{C}/^{13}\text{C}$ ratio approaches the CN-cycle equilibrium value of ~ 4 (e.g. Suntzeff & Smith 1991; Shetrone et al. 1993; Shetrone 1996; Carretta et al. 2000; Gratton et al. 2000; Keller et al. 2001).

Since the realisation that both $^{12}\text{C}/^{13}\text{C}$ and $^{12}\text{C}/^{14}\text{N}$ ratios decrease with increasing luminosity along the RGB (e.g. Gilroy & Brown 1991; Kraft 1994; Charbonnel et al. 1998; Gratton et al. 2000; Keller et al. 2001), a variety of mechanisms to produce extra mixing between core and envelope on the RGB have been proposed to explain the observations (see, e.g., Angelou et al. 2011, for a recent summary). Of these, the thermohaline instability pointed out by Charbonnel & Zahn (2007b, see also Eggleton et al. 2006 who first noted the molecular weight inversion that causes it) appears most promising. The instability sets in beyond the RGB “bump”—the point in the RGB luminosity function where the outward progress of the H-burning shell encounters the compositionally uniform layers resulting from the deepest extent of convection during the first dredge-up. It results from the mean molecular weight of this region exceeding that of a layer just above the H-burning shell in which the mean molecular weight is reduced by the reaction $^3\text{He}(^3\text{He}, 2\text{p})^4\text{He}$ (Abraham & Iben 1970; Ulrich 1971).

Several recent studies have discussed thermohaline mixing and its apparent success in comparisons of model predictions with observed abundances on the RGB (e.g. Charbonnel & Zahn 2007b; Recio-Blanco & de Laverny 2007; Stancliffe et al. 2009; Charbonnel & Lagarde 2010; Cantiello & Langer 2010; Denissenkov 2010; Smiljanic et al. 2010; Tautvaišienė et al. 2010b; Angelou et al. 2011). Thermohaline mixing on the RGB changes both the surface $^{12}\text{C}/^{13}\text{C}$ and $^{12}\text{C}/^{14}\text{N}$ ratios after the end of the first dredge-up, in contrast to classical models that do not include extra mixing. In principle, comparison of predicted and observed values of both ratios should provide a more stringent test of the theory than either ratio alone. The $^{12}\text{C}/^{13}\text{C}$ ratio can usually be determined from CN molecular features for RGB stars with a precision of $\sim 20\%$ or so—useful for comparison with and constraining models. Unfortu-

nately, assessment of photospheric N abundances is not so precise and usually has to rely on similar CN features. The N abundance then also depends on the derived C abundance through molecular equilibrium, and the resulting uncertainties in the C/N ratio can be quite large and rarely below 0.2 dex. The use of field RGB stars for confronting model predictions is also hampered by their uncertain masses and evolutionary phases, especially near spectral type K0 where the evolutionary tracks of clump stars of different mass overlap with those of first ascent stars.

Here, we draw attention to nearby evolved active binary stars, whose masses and evolutionary phases can generally be much better constrained than for field stars, as offering potentially valuable laboratories for further study of dredge-up and post dredge-up mixing. Denissenkov et al. (2006) have also piqued interest in these stars through theoretical modelling that indicates extra mixing on the RGB might be induced by tidal spin-up. In this context, the nearby (26 pc) old disk giant λ And presents an interesting case: it is a mildly metal-poor first-ascent G8 III-IV star at an evolutionary phase in which CN-cycle products should have just appeared at its surface due to first dredge-up (Savanov & Berdyugina 1994; Donati et al. 1995; Ottmann et al. 1998; Tautvaisienė et al. 2010a; further characteristics are listed in Table 1). Other than its close binarity, it is similar to members of the sample of mildly metal-poor ($[\text{Fe}/\text{H}] \sim -0.5$) disk giants that Cottrell & Sneden (1986) found to have *unevolved* (approximately solar) C/N ratios, but lower $^{12}\text{C}/^{13}\text{C}$ ratios of ~ 10 –30 than predicted by canonical models and reminiscent some of those seen in earlier studies of field giants toward solar metallicity (Lambert & Ries 1981; Kjaergaard et al. 1982). The unevolved C/N ratios contrasted with the study of slightly more massive giants in the solar metallicity cluster M67 by Brown (1987), which found a palpable decline of C/N on the ascent of the giant branch. Cottrell & Sneden noted that the C/N ratios in the old disk giants “have probably remained unchanged since their formation”. Standard dredge-up predictions for red giants of mass $\lesssim 1M_{\odot}$ thought typical of the Cottrell & Sneden sample indeed indicate little change in the surface C/N ratio, but also only mild reduction in the $^{12}\text{C}/^{13}\text{C}$ ratio to values $\gtrsim 30$. The observed low $^{12}\text{C}/^{13}\text{C}$ ratios suggest that additional mixing of CN-processed material has occurred further to that of classical model predictions, but of a nature as not to change the surface C/N ratio. Mixing of such a characteristic was initially proposed by, e.g., Dearborn & Eggleton (1977); Sweigart & Mengel (1979); Hubbard & Dearborn (1980); Lambert & Ries (1981) in order to explain ^{13}C rich stars such as Arcturus, which also has $[\text{C}/\text{N}] \sim 0$.

Of the studies to date confronting thermohaline mixing model predictions with observations, little attention has been given to mildly metal-poor stars with masses $< 1M_{\odot}$. In §2 we use a precise *X-ray* measurement of the surface C/N abundance of λ And to show that it is typical of old disk giants from the Cottrell & Sneden (1986) sample. In §3, we

combine this measurement with the $^{12}\text{C}/^{13}\text{C}$ assessments of Tautvaišienė et al. (2010a) and Savanov & Berdyugina (1994) and compare the results with predictions from a state-of-the-art stellar evolutionary model including thermohaline mixing.

2. Observations and Analysis

We estimate the surface C/N abundances from emission lines of H-like ions of C and N seen in *Chandra* Low Energy Transmission Grating (LETG) X-ray spectra of λ And. Our analysis follows those presented previously by Drake (2003b) and Drake & Sarna (2003), to which we refer the reader for details; see also Schmitt & Ness (2002). Our method exploits the insensitivity of the relative intensities of the C VI $\lambda 33.7$ and N VII $\lambda 24.7$ lines in active stars to the coronal temperature structure: the line ratio depends essentially only on the relative C and N abundances.

Chandra X-ray spectra of λ And were obtained on 2002 July 22 and 23 (ObsID 2558 and 3722, respectively) in two separate observations of 50 ks each, using the LETG and High Resolution Camera spectroscopic (HRC-S) detector in its standard instrument configuration. Data were obtained from the Chandra Data Archive¹, and were reduced using the CIAO software package version 3.2. This latter processing included filtering of events based on observed signal pulse-heights to reduce background. Spectra were analysed using the PINTofALE² IDL³ software suite (Kashyap & Drake 2000).

XMM-Newton observed λ And on 2001 January 26 for 32 ks. Data were processed and reduced using standard *XMM-Newton* Science Analysis System software, and RGS spectra were extracted with the RGSPROC task. Spectral line fluxes were measured by fitting line profiles using the CORA program (Ness & Wichmann 2002). Measured lines intensities for both *Chandra* and *XMM-Newton* spectra are listed in Table 2.

The LETG spectrum of λ And for the wavelength range that includes both the N VII and C VI lines is illustrated in Fig. 1, alongside spectra of the single giant β Ceti (K0 III) and the unevolved dwarf ϵ Eri (K2 V). The latter two stars were also used by Drake & Sarna (2003) as examples of spectra of evolved and unevolved comparison stars. Simple visual inspection reveals that the λ And subgiant C/N line strength ratio is similar to that of ϵ Eri, and is very unlike that of the evolved β Ceti. More formally, Drake (2003b) showed that the

¹<http://asc.harvard.edu/cda>

²PINTofALE is freely available from <http://hea-www.harvard.edu/PINTofALE/>

³Interactive Data Language, Research Systems Inc.

C/N abundance ratio by number, $n(C)/n(N)$, is given by

$$\frac{n(C)}{n(N)} = 1.85 \times \frac{(I_C/A_{Ceff})}{(I_N/A_{Neff})}, \quad (1)$$

where I_C and I_N are the number of counts in the C VI (24.7 Å) and N VII (33.7 Å) lines, and A_{Ceff} and A_{Neff} are the effective area normalising factors (in cm²) at the appropriate wavelengths of the C and N transitions, respectively. Applying this formula to the λ And observations gives $n(C)/n(N) = 3.1 \pm 0.75$ and 4.3 ± 0.6 for ObsIDs 2558 and 3722, respectively; co-adding the observations leads to $n(C)/n(N) = 3.8 \pm 0.6$, or $[C/N] = -0.03 \pm 0.07$ on the Asplund et al. (2009) solar abundance scale, which we adopt as our final result. Additional systematic errors arising from uncertainties in instrument calibration and atomic data are expected to be $\lesssim 10\%$ (Drake 2003b).

In light of the now well-documented chemical fractionation related to element first ionization potential (FIP) that occurs between the coronae and photospheres of stars (e.g. Drake 2003a), it might be questioned whether the coronal C/N ratio derived here is representative of that of the underlying photosphere. Drake (2003b) studied the coronal C/N ratio in the active binary V711 Tau and concluded that C and N are not fractionated to any significant extent with respect to the photosphere. This is expected based on the similar high FIPs of these elements (11.3 and 14.5 eV for C and N, respectively). While we cannot rule out relative fraction among C and N with absolute certainty, we therefore consider our derived C/N abundance ratio to be directly applicable to the photosphere of λ And.

Our C/N ratio is in good agreement with the earlier estimates of $[C/N] = -0.24$ and -0.25 (adjusted to the Asplund et al. (2009) scale) by Savanov & Berdyugina (1994) and Tautvaišienė et al. (2010a), bearing in mind the “0.2-0.3 dex” uncertainty they assess for their C/N abundance ratio.

3. Discussion

The currently favoured solar (unevolved) $n(C)/n(N)$ abundance ratio is 3.98 (Asplund et al. 2009), with stated uncertainties of 0.05 dex for both C and N. C/N ratios for galactic field stars are known with somewhat less precision. Galactic disk dwarfs show $[C/N] = 0$ down to metallicities of $[Fe/H] = -0.4$, though with some scatter attributable to uncertainties in N abundances determined from weak N I lines (Reddy et al. 2003). Mishenina et al. (2006) find no significant trend of C/N with $[Fe/H]$ over a similar metallicity range for a sample of 177 disk giants, indicating that the post-dredge-up ratio also evolves similarly for solar metallicity and mildly metal-poor stars.

Our observed C/N ratio for λ And is perfectly consistent with an unevolved composition, showing no signs of post dredge-up change. In contrast, Savanov & Berdyugina (1994) and Tautvaišienė et al. (2010a) found an unambiguous signature of dredge-up in the carbon isotope ratio for which they derived $^{12}\text{C}/^{13}\text{C} = 20 \pm 5$ and 14, respectively. In the following we adopt the average of these values, $^{12}\text{C}/^{13}\text{C} = 17 \pm 5$, though our conclusions would be unchanged regardless of whether we adopted either result. This CN signature of λ And is typical of the old disk giants analysed by Cottrell & Sneden (1986), in keeping with its mild metal deficiency credential ($[\text{Fe}/\text{H}] = -0.5$ on the Asplund et al. 2009 scale; Savanov & Berdyugina 1994; Donati et al. 1995; Ottmann et al. 1998; Tautvaišienė et al. 2010a).

By comparison with model evolutionary tracks, we can estimate the evolutionary state of λ And. We used a version of the STARS code (Eggleton 1971; Pols et al. 1995; Stancliffe & Eldridge 2009, and references therein) with updated opacities (Eldridge & Tout 2004; Stancliffe & Glebbeek 2008) and nucleosynthesis routines (Stancliffe et al. 2005; Stancliffe 2005) to generate evolutionary tracks from the main sequence for stars with metallicity $z = 0.008$ and masses in the range $0.7\text{--}1.7 M_{\odot}$. Thermohaline mixing was included in these models following Stancliffe et al. (2009), using the prescription of Kippenhahn et al. (1980), with the diffusion coefficient multiplied by a factor of 1000, following Charbonnel & Zahn (2007b). The resulting evolutionary tracks are illustrated in Figure 2, together with the data point for λ And (see Table 1). Also shown is the locus describing the evolutionary stage at which stars of different mass essentially reach the end of the first dredge-up. While dredge-up end is formally defined as the point at which the convection zone reaches its deepest penetration in mass, we defined it here as the point at which the surface $^{12}\text{C}/^{13}\text{C}$ ratio reaches within 5% of what would be the final RGB values in the absence of additional mixing processes; after this, canonical models predict their surface abundances remain constant until later dredge-up phases. We use this looser definition of the end of dredge-up to illustrate that the $^{12}\text{C}/^{13}\text{C}$ ratio is predicted to reach close to its final value significantly below the RGB bump.

Figure 2 shows that λ And lies a factor of 2-3 in luminosity below horizontal branch tracks characterising the clump, and so must be a first ascent giant (see also the extensive discussion of Donati et al. 1995). It also lies just beyond the “end” of first dredge-up; using the STARS tracks, we estimate that this phase was completed ~ 50 Myr ago, in qualitative agreement with the earlier assessment of Donati et al. (1995). We also estimate from these evolutionary tracks a mass for λ And of $1.0 \pm 0.2 M_{\odot}$, which compares favourably with the spectroscopic estimate based on $\log g$ and the radius (Table 1) of $1.3^{+1.0}_{-0.6} M_{\odot}$. This is consistent, within experimental error, with the estimate of Donati et al. (1995); our slightly larger value is mostly due to our adopted surface gravity being higher (see analyses by Savanov & Berdyugina 1994; Ottmann et al. 1998; Tautvaišienė et al. 2010a).

The value of the precise X-ray measurement of C/N is apparent in Figure 3, which compares the observed C isotope and C/N ratios for λ And with predictions from canonical evolution models past the first dredge-up but with no additional post-dredge-up mixing (Schaller et al. 1992; Vandenberg 1992; Girardi et al. 2000). In accordance with well-established dredge-up results, models predict a reduction in $^{12}\text{C}/^{13}\text{C}$ with increasing mass, with only very mild reductions for the lowest mass stars. Also shown are the observed ratios for the old disk giants from Cottrell & Sneden (1986). This kinematically-selected sample comprises low mass stars with $M \lesssim 1M_{\odot}$, very much like λ And. λ And and the old disk giants have C/N ratios more or less in agreement with the models, but have much lower $^{12}\text{C}/^{13}\text{C}$ ratios. There is some selection effect in the latter group because stars with higher $^{12}\text{C}/^{13}\text{C}$ ratios tend to be represented only by lower limits, though this applies only to 4 out of the 34 stars in the Cottrell & Sneden (1986) sample; no $^{12}\text{C}/^{13}\text{C}$ data are available for a further 8 stars. Statistically, the majority of the Cottrell & Sneden (1986) sample are expected to be core He-burning stars, since this evolutionary phase lasts several times longer than the first RGB ascent. The problem with the abundance ratios for these old disk giants is that they exhibit much more extreme processing of ^{12}C to ^{13}C than the models, but essentially no processing of ^{13}C to ^{14}N .

The STARS models with thermohaline mixing predict changes in the surface $^{12}\text{C}/^{13}\text{C}$ and C/N ratios above the RGB ‘bump’. The $^{12}\text{C}/^{13}\text{C}$ vs. C/N loci from the main-sequence to the RGB tip for four models corresponding to different stellar masses are illustrated in Figure 4. The most relevant of these for the sample under consideration are the 0.7 and $1.0M_{\odot}$ ones. While the Cottrell & Sneden sample has systematically higher C/N ratios on average than the models by about 50%, a systematic error of this magnitude in the observed values probably cannot be ruled out given the 0.2 dex uncertainty on each. The range of observed $^{12}\text{C}/^{13}\text{C}$ ratios is instead in very good agreement with the thermohaline mixing predictions.

At face value, the generally reasonable agreement between observed and model abundances for the metal-poor old disk star sample is encouraging. However, λ And does present a problem. Its C/N ratio is significantly higher than model predictions, though for a single object such a discrepancy might be attributed to cosmic variance. More important is the evolutionary phase at which the thermohaline mixing begins to affect the surface $^{12}\text{C}/^{13}\text{C}$ ratio. This is above the RGB bump. Tautvaišienė et al. (2010a) pointed out that λ And instead lies well below the bump, as demonstrated in Figure 2, and indicates that $^{12}\text{C}/^{13}\text{C}$ is anomalous earlier in its evolution, and perhaps immediately following dredge-up.

One possible source of the anomaly is contamination from its companion. There is no direct observational information to assess with certainty the nature of the companion, though

Donati et al. (1995) presented cogent arguments based on the asynchronicity of the rotation and orbital periods of λ And to rule out a white dwarf nature for the secondary. Such a star might otherwise have contaminated the current primary with carbon-rich material during its asymptotic giant branch (AGB) phase. However, finding a companion that is able to provide material of a suitable composition is difficult. Low-mass AGB stars that undergo the third dredge-up become rich in carbon-12, yet do not produce much in the way of carbon-13 and nitrogen-14. For example, Karakas & Lattanzio (2007) find that a $1.5M_{\odot}$ star of $Z = 0.004$ produces ejecta with a $^{12}\text{C}/^{13}\text{C}$ ratio of over 100 and a C/N ratio of about 10. Stancliffe & Jeffery (2007) find similar values for the ejecta of a $1.5M_{\odot}$ star of $Z = 0.008$. These values are too high to match those observed in λ And, even if one allows for the dilution of any accreted material via mixing with the pristine material of the receiving star. One may wish to invoke some sort of extra mixing processes at work during the AGB in order to lower these values. The physical nature of this extra mixing process is unknown. It is unlikely to be thermohaline mixing, as this has been shown unable to produce $^{12}\text{C}/^{13}\text{C}$ ratios as low as 10 at lower metallicity than that of λ And even though it is more effective at low metallicity (Stancliffe 2010). There is also debate about whether this is actually required in low-mass AGB stars (see Busso et al. 2010 and Karakas et al. 2010 for opposite sides of this debate). Appealing to a higher mass companion, one that underwent hot bottom burning on the AGB, is also unlikely to help: the models of Karakas & Lattanzio (2007) suggest that these would produce $^{12}\text{C}/^{14}\text{N}$ less than 1—too low to match the observations.

We also note here a fundamental difference between λ And and the subgiants in the globular clusters NGC 6752 and 47 Tuc that were found to have $^{12}\text{C}/^{13}\text{C} \lesssim 10$ by Carretta et al. (2005): unlike λ And these stars also have depleted C and enhanced N abundances. Carretta et al. (2005) interpreted these abundances as the signature of contamination by mass loss from intermediate-mass AGB stars.

Recently, the C isotope and C/N ratios have been estimated for two additional RS CVn-type binaries, 29 Dra and 33 Psc. Barisevičius et al. (2010, 2011) find similar C/N ratios ($[\text{C}/\text{N}] \sim -0.25$) to the Tautvaišienė et al. (2010a) value for λ And, but find $^{12}\text{C}/^{13}\text{C} = 16$ for 29 Dra and 30 for 33 Psc. The latter is “normal” for a post-dredge-up star, and indeed 33 Psc, like λ And, lies below the bump luminosity (Barisevičius et al. 2011) and is not expected to have experienced additional post-dredge-up mixing episodes. The isotope ratio for 29 Dra is instead similar to that of λ And. Based on the atmospheric parameters of Barisevičius et al. (2010), 29 Dra is probably cooler by ~ 100 K and more luminous by 0.05 dex than λ And, and therefore lies slightly above and to the right of λ And in Figure 2. Nevertheless, it is likely still located just below the luminosity bump and would therefore appear anomalous in terms of the $^{12}\text{C}/^{13}\text{C}$ ratio.

λ And, and likely 29 Dra, then seem to present a challenge to the current description of thermohaline mixing as the controlling factor in post-dredge-up surface abundance changes. While this mechanism appears generally successful in explaining post-dredge-up CNO and light element surface abundances (§1), the diffusion coefficient dictating the rate of mixing is not well-constrained (Charbonnel & Zahn 2007b; Denissenkov 2010). Three-dimensional numerical simulations of thermohaline convection by Denissenkov & Merryfield (2011) and Traxler et al. (2011) find a mixing rate that is at least a factor of 50 lower than that required by models to match observed RGB abundance changes. In essence, the penetrating structures of one fluid into the other that effect the mixing, commonly referred to as “salt fingers”, have a length-to-width aspect ratio in the simulations that is too small. Both studies concluded that thermohaline convection driven by ^3He burning is unlikely to be the sole mechanism of extra mixing on the RGB and must be enhanced or augmented by other processes. Interestingly for the magnetically-active λ And, Denissenkov & Merryfield (2011) suggested strong toroidal magnetic fields arising from differential rotation in the radiative zone might enable more growth of thicker fingers. Alternatively, Charbonnel & Zahn (2007a) note that strong magnetic fields can act to damp the thermohaline instability and suggest this as a means of suppressing extra mixing in the RGB descendents of Ap stars.

Even if the magnetic activity of λ And might provide some assistance to the process, it does not solve the problem that its surface abundances are changed before the predicted on-set of the thermohaline instability. Rotation-driven mixing, once thought the main abundance-modifying mechanism on the RGB, also would not help for similar reasons, although Palacios et al. (2006) have essentially ruled the process out for producing significant surface abundance modifications. One possible alternative is the magnetic mixing process proposed by Busso et al. (2007), in which buoyant flux tubes generated in a stellar dynamo operating near the hydrogen-burning shell transport processed matter upward into the convective envelope. Again, the challenge for such a mechanism to work for λ And would be to bring sufficient ^{13}C -rich material to the surface so soon after dredge-up.

We are otherwise drawn back to the discussion of the ^{13}C -rich giants by Lambert & Ries (1981), who reasoned that some ^{13}C must be removed from the CN-processing zone prior to conversion through proton capture to ^{14}N on the main sequence (see also, e.g. Dearborn & Eggleton 1977, Sweigart & Mengel 1979, and the “magnetic mixing” of Hubbard & Dearborn 1980). Thermohaline mixing seemed to solve much that was raised in that discussion, though in the light of the conclusions of Denissenkov & Merryfield (2011), the odd exception such as λ And and 29 Dra also seems to point to other effects. Existing studies of rotationally-driven mixing and other mechanisms do not yet generally include aspects such as close binarity and strong magnetic fields that distinguish λ And from other stars in RGB abundance surveys. Theoretical models including tidal interaction and spin-up of giants in RS CVn-type binaries

developed by Denissenkov et al. (2006) present an interesting exception.

Denissenkov et al. (2006) found evolutionary models with tidal spin-up caused by a close companion to exhibit large excursions of $M_V \sim 0.7\text{--}0.8$ at the luminosity bump, and evolution through this phase consequently took 50% longer than for single stars. They cited this as a possible explanation for the propensity of known tidally-interacting binaries to comprise one component on the lower part of the RGB. The models assumed synchronization of orbital and rotation periods had been established. λ And is notoriously unsynchronized, but it lies only just below the bump luminosity. Were such large bump excursions to occur, they would allow λ And and 29 Dra to be “post-bump” stars, lying on the downward lower luminosity excursion. The extended stay at this point in its evolution would also provide greater opportunity for mixing of ^{13}C -rich material into its convection zone by rotation, thermohaline or other mixing process.

The question then arises why λ And and 29 Dra exhibit C isotope ratio anomalies but 33 Psc does not? Barisevičius et al. (2011) pointed to the low activity of 33 Psc compared to that of λ And and 29 Dra. The orbital period of 33 Psc is 79.4 days (Harper 1926) though its rotation velocity is not constrained. The orbital period of 29 Dra is much longer, 904 days, but it has a rotation period of about 30 days (Hall et al. 1982; Zboril & Messina 2009), which is shorter than that of λ And (54 days), and based on activity indices is likely a faster rotator than 33 Psc. Since 29 Dra is a much wider binary than either λ And or 33 Psc, tidal interactions would appear not to be the primary factor governing the isotope anomaly, and instead rotation and activity appear to be the culprits.

4. Conclusions

A precise X-ray measurement of H-like C and N formed in the corona of the G8 III-IV primary of the RS CVn-type binary λ And has revealed a solar C/N abundance ratio that is essentially unchanged since the star was formed. This is in qualitative agreement with evolutionary calculations for such low-mass stars ($\lesssim 0.9M_\odot$), but is quite inconsistent with its photospheric ratio $^{12}\text{C}/^{13}\text{C} = 14$ (Savanov & Berdyugina 1994; Tautvaišienė et al. 2010a) that is much lower than predicted by theory. This abundance pattern is typical of the old disk giants first brought to prominence by Cottrell & Sneden (1986). λ And is a first ascent red giant that underwent dredge-up only ~ 50 Myr ago; its anomalously low $^{12}\text{C}/^{13}\text{C}$ has appeared immediately after dredge-up. We echo the conclusions of Tautvaišienė et al. (2010a) that extra mixing on the RGB in magnetically-active low-mass stars like λ And and 29 Dra appears to act below the luminosity function bump, in contradiction with current thermohaline mixing models. Magnetic flux tube buoyant mixing (Busso et al. 2007) would

appear to warrant more detailed investigation. Evolutionary models of tidally-interacting binaries by Denissenkov et al. (2006) that predict large luminosity excursions at the bump might also allow λ And to be a “post-bump” giant and alleviate its otherwise precociously diminished C isotope ratio. Such a mechanism would appear to be less promising for wider binaries such as 29 Dra.

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Table 1. Summary of parameters of the λ And primary

Spec. Type	Dist (pc) ^a	P_{rot} (d) ^b	T_{eff} (K) ^c	$\log g$ ^c	[Fe/H] ^c	M (M_{\odot}) ^d	R (R_{\odot}) ^e	$\log L/L_{\odot}$ ^f	L_X (erg s ⁻¹) ^g
G8III-IV+	25.8	54	4800 ± 100	2.75 ± 0.25	-0.5	$1.3^{+1.0}_{-0.6}$	7.0 ± 0.7	1.37 ± 0.04	2.95×10^{30}

^a*Hipparcos* distance from van Leeuwen (2007) .

^bLandis et al. (1978)

^cAdopted here based on estimates from Savanov & Berdyugina (1994); Donati et al. (1995); Ottmann et al. (1998); Soubiran et al. (2008); Tautvaišienė et al. (2010a); [Fe/H] is expressed relative to the solar composition $Fe/H = 7.50$ (Grevesse & Sauval 1998; Asplund et al. 2009).

^dSpectroscopic mass from L_{bol} , T_{eff} and $\log g$.

^eSpectroscopic radius based on L_{bol} and T_{eff} .

^fTautvaišienė et al. (2010a); uncertainty estimated here based on the Alonso et al. (1999) bolometric correction change for a 100 K temperature uncertainty at our adopted T_{eff} .

^gDempsey et al. (1993), based on *ROSAT* All-Sky Survey observations, updated to the *Hipparcos* distance of van Leeuwen (2007).

Table 2. Measured line intensities (in counts) for λ And

λ (Å)	Ion	Chandra			XMM-Newton		Transition
		ObsID 2558	ObsID 3722	A_{eff}	RGS2	A_{eff}	
24.779	N VII	163.1±34	211.7±36	15.2	136.1 ± 19	46.7	(2p) $2P_{3/2} \rightarrow (1s) 2S_{1/2}$
33.734	C VI	205.5±27	376.1±35	11.6	138.7 ± 18	22.6	(2p) $2P_{3/2} \rightarrow (1s) 2S_{1/2}$

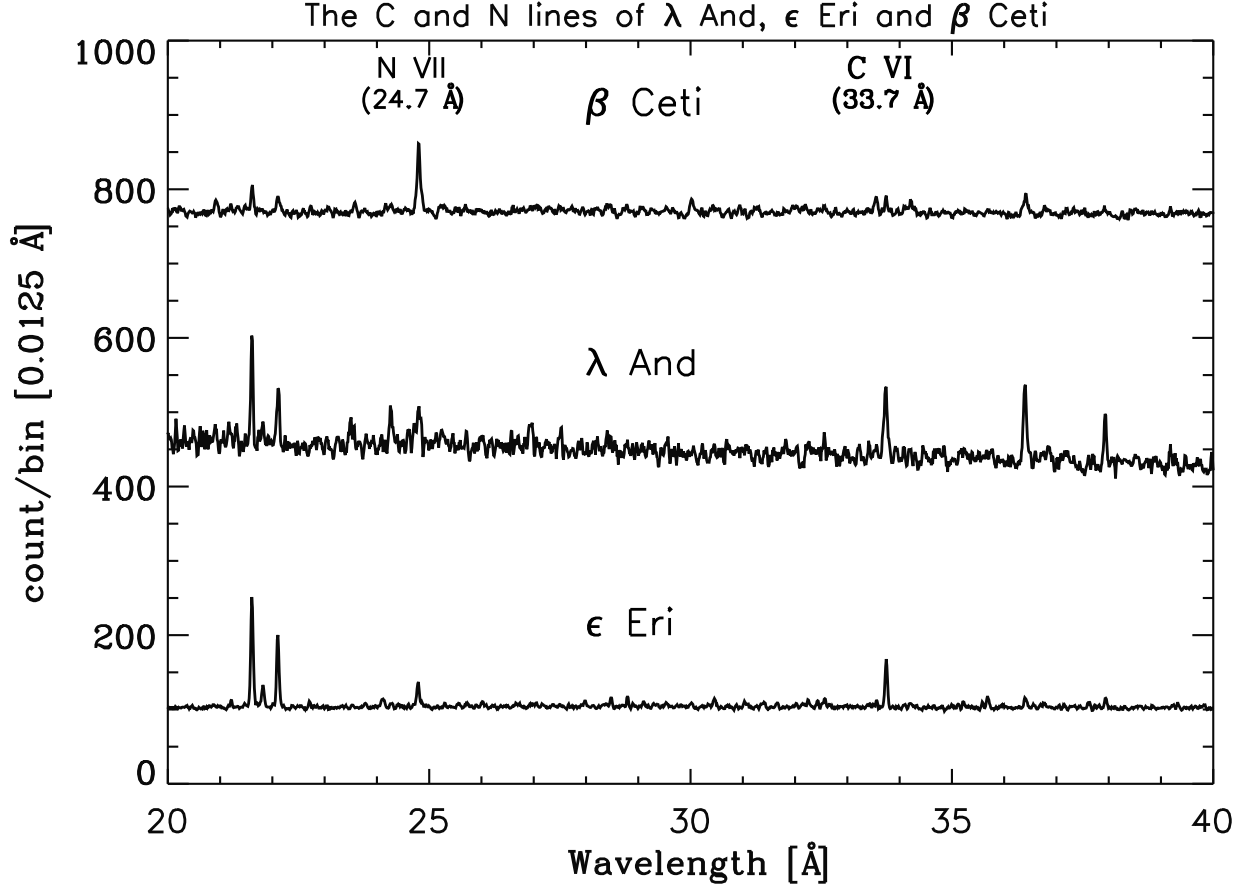


Fig. 1.— The λ And LETGS spectrum in the 20-40 Å region, showing C and N lines, compared with β Ceti (evolved) and ϵ Eri (unevolved). The λ And spectrum has been multiplied by 3 for clarity. The λ And C and N line strengths are in a similar ratio to that of the unevolved dwarf ϵ Eri and show no significant signs of the C depletion evident in the spectrum of β Ceti.

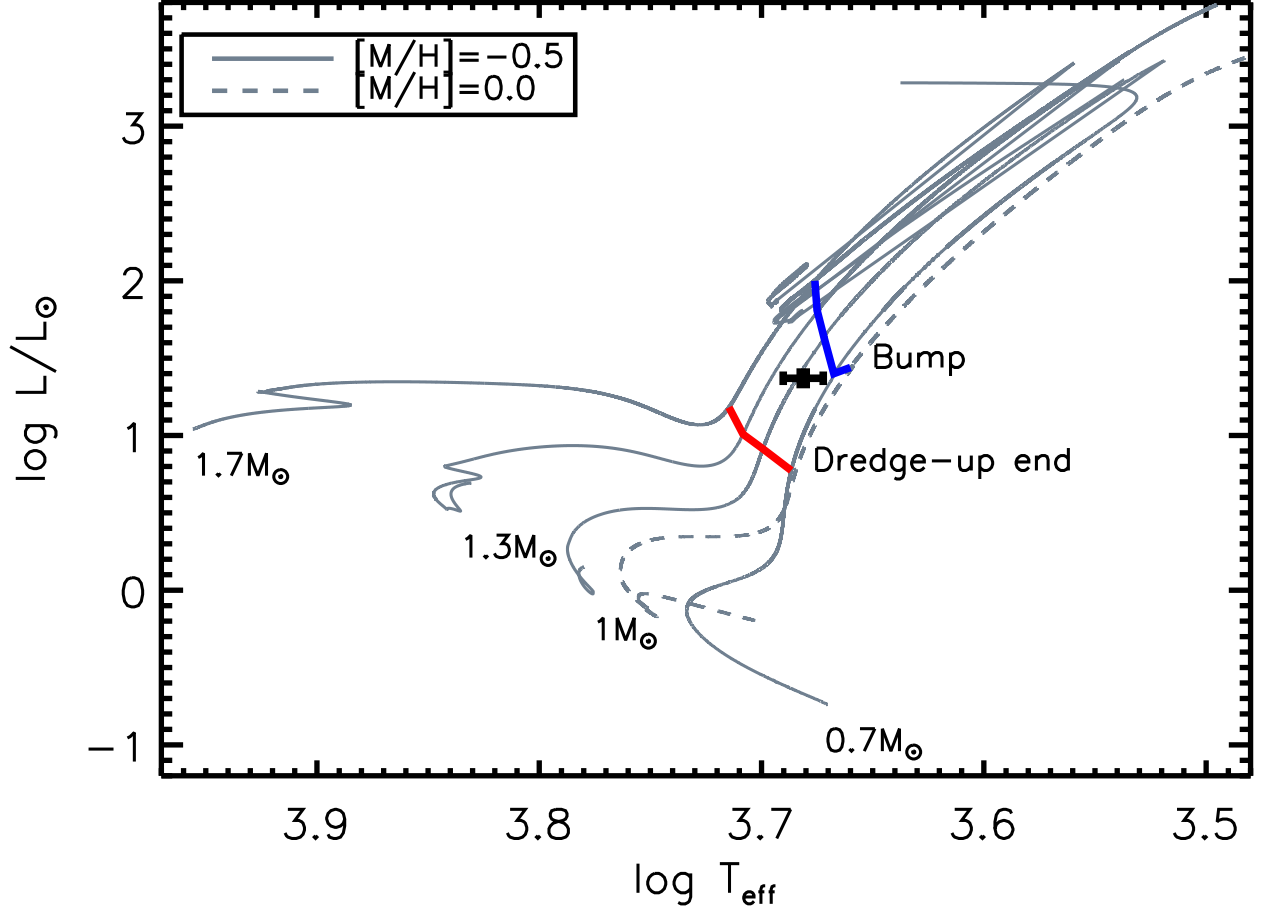


Fig. 2.— Comparison of the effective temperature and luminosity of λ And with evolutionary tracks computed using the STARS program for metallicity $Z = 0.008$ (see text). “Dredge-up end” indicates the point at which the surface abundances are within 5% of their final post-dredge-up values. λ And finished dredge-up about 50 Myr after this point.

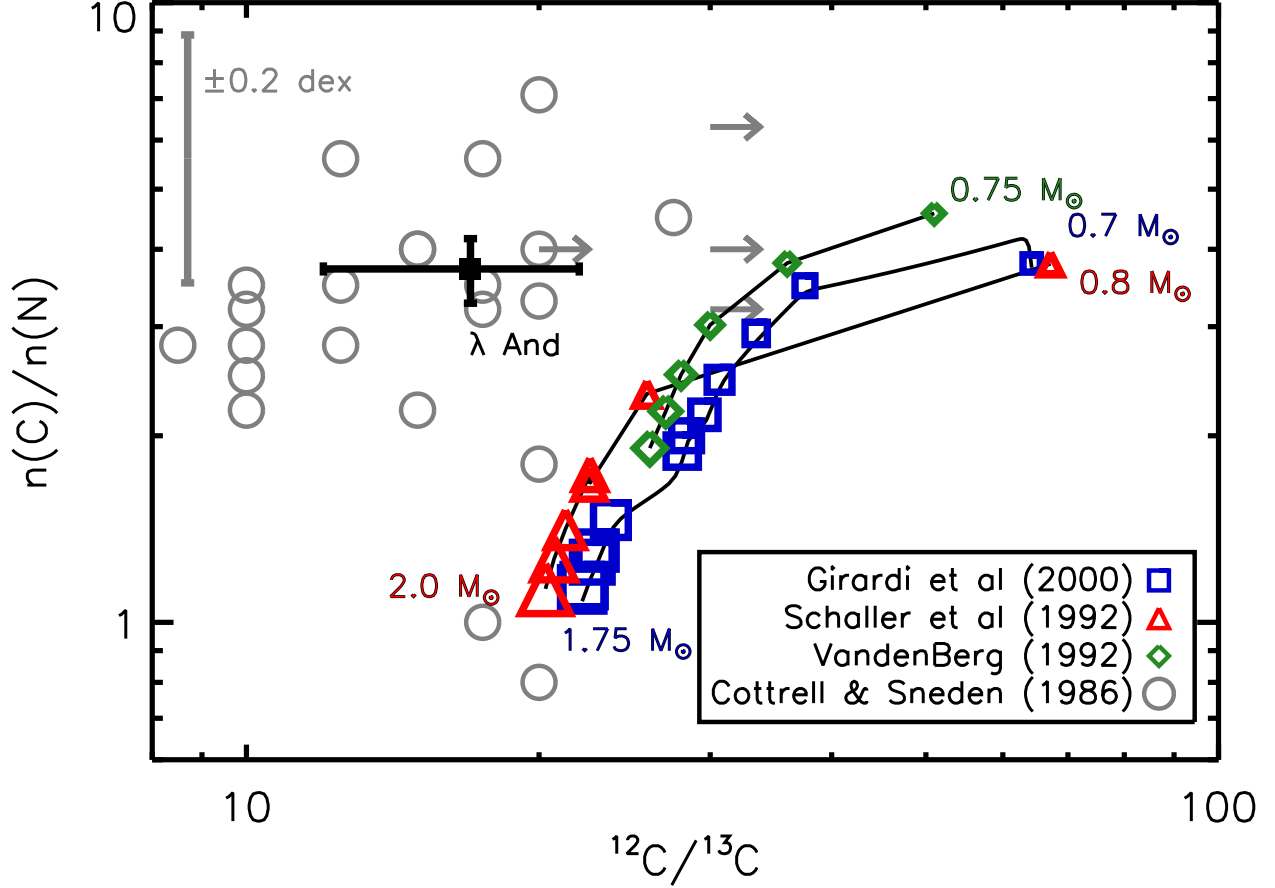


Fig. 3.— Model predictions of the post-dredge-up surface C/N abundance ratio (by number) as a function of the $^{12}C/^{13}C$ ratio for stars of different mass (denoted by symbol size), from Schaller et al. (1992); Vandenberg (1992) and Girardi et al. (2000). Also shown are the $^{12}C/^{13}C$ and C/N ratios estimated for old disk giants by Cottrell & Sneden (1986), together with a representative 0.2 dex error bar. The X-ray λ And C/N ratio is illustrated together with the $^{12}C/^{13}C$ ratio from Tautvaišienė et al. (2010a).

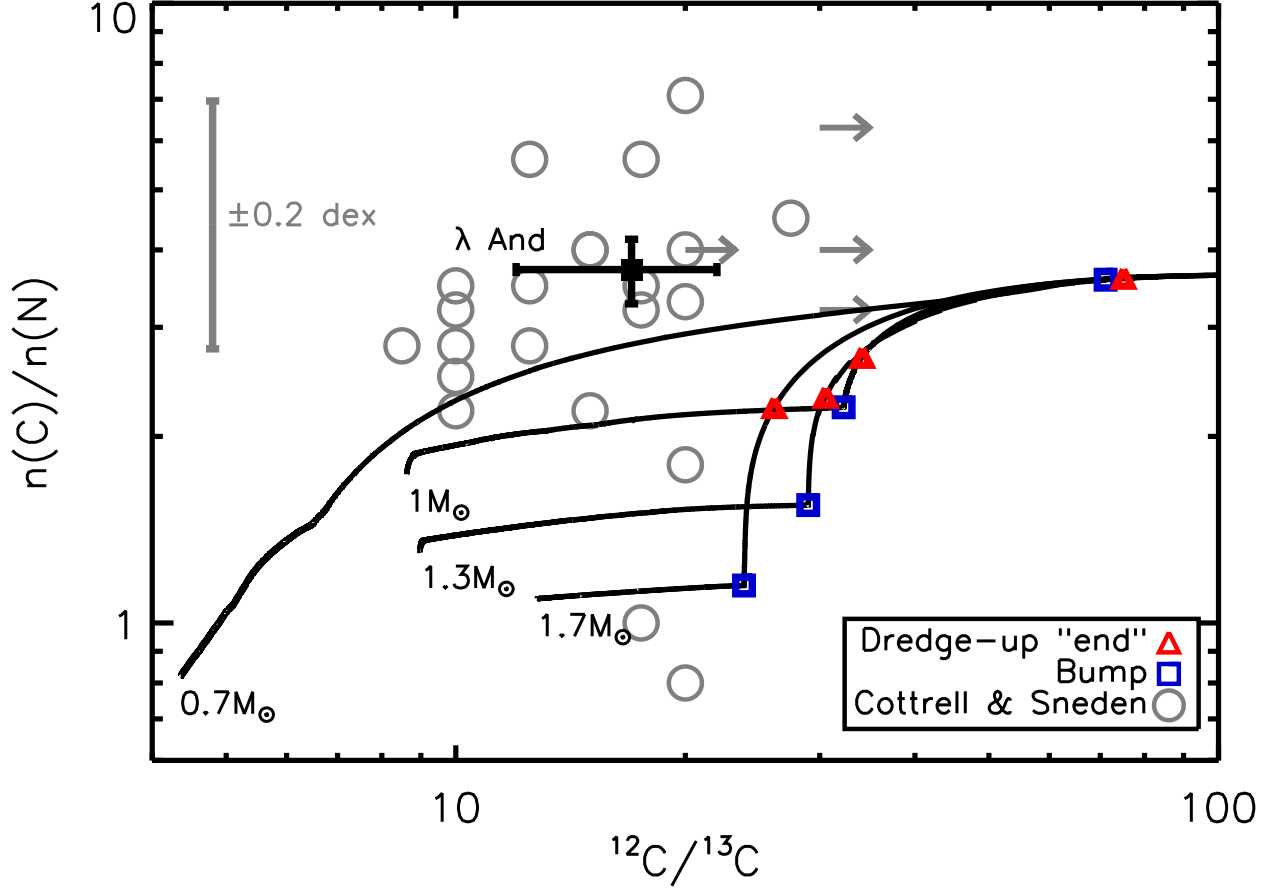


Fig. 4.— Similar to Figure 3 but illustrating STARS predictions of the post-dredge-up surface $^{12}\text{C}/^{13}\text{C}$ vs C/N trajectories of models including thermohaline mixing on the RGB compared with the ratios estimated for old disk giants by Cottrell & Sneden (1986). The X-ray λ And C/N ratio is illustrated together with the $^{12}\text{C}/^{13}\text{C}$ ratio from Tautvaišienė et al. (2010a). Evolution from the main-sequence toward the tip of the RGB corresponds to progress along the loci from right to left.